A CHARACTERIZATION OF UNDERSEA NEUTRON AND CAPTURE GAMMA SIGNATURES RESULTING FROM SPECIAL NUCLEAR MATERIAL ON A MARITIME VESSEL

Midshipman 2nd Class Elizabeth J. Troy, Commander Travis Chapman, USN, and Assistant Professor Marshall Millett

PO Box 14935 Annapolis, MD 21412, m206426@usna.edu; tchapman@usna.edu; millett@usna.edu

Abstract:

Special Nuclear Materials (SNM) located aboard ships emit radiation that may be detectable in the undersea environment. An Unmanned Underwater Vehicle (UUV) could be equipped with detection capabilities to determine whether commercial or private vessels are carrying SNM prior to reaching port. Additional research is needed improve such a UUV's ability to detect and discriminate between types of SNM and reduce false-positive detections. This research builds on past work by C. T. McKay to provide a higher fidelity characterization of detectable radiation signatures from SNM in the undersea environment with a focus on plutonium-bearing SNM. ^{252}Cf will be used to produce a similar neutron energy distribution as plutonium. A carbon steel plate will simulate the effect of vessel structural materials to produce representative neutron and capture gamma radiation profiles. The transport of both neutron and capture gammas is considered and compared. The neutron signature is reduced due to absorption in seawater. However, neutron capture by seawater produces high-energy gammas. These high-energy capture gammas are not attenuated as significantly as neutrons, have a distinct energy profile, and may be readily detected at longer distances in seawater. A Sodium Iodide detector and a High Purity Germanium detector will detect the gamma population at set distances from the source and this signature will be compared with the neutron signature detected with a Helium-3 detector. The results will provide insight into preferable methods of detection and discrimination of capture gamma signatures to identify SNM in the maritime environment.

Introduction

Special Nuclear Material (SNM) is defined by Title I of the Atomic Energy Act of 1954 as plutonium, uranium-233, or uranium enriched in the isotopes uranium-233 or uranium-235 [1], which can be used for nuclear weapons. When they decay they emit alphas, betas, primarily lower energy gamma rays, and, in the case of plutonium, neutrons. Knowing these decay mechanisms, the presence and type of these materials can be assessed using neutron detection and/or gamma spectrometry.

Due to the threat posed by SNM and other illicit nuclear materials that could enter the U.S., there are ongoing efforts to improve our ability to detect SNM at ports of entry and the broader maritime domain. For example, the U.S. Domestic Nuclear Detection Office's Large Scale Detection Systems Program aims at improving scanning coverage using radiation portal monitors at land border crossings and seaports [2].

Improvements in our ability to conduct real time scanning of vessels have included the design of buoy-mounted sensors and the development of the SuperMISTI standoff detection system [3]. The SuperMISTI system is capable of detecting, identifying, and providing imaging for gamma sources at operationally practical distances [4]. Such developments may offer a method of interrogating suspect vessels prior to entry in the terminal without affecting the flow of commerce.

Neutrons present an interesting detectable signal in three respects: the natural neutron background is generally low and predictable, neutron shielding methods are more challenging than gamma shielding, and the ultimate free neutron end state is absorption, which often results in the emission of very high-energy gammas, far beyond the energy of the typical background gamma spectrum. These high-energy capture gammas also have a lower probability of interacting with matter and consequently a longer mean free path, making them harder to shield. Detection of neutron sources via capture gamma signal has been proposed in both a border security context and in the undersea environment [5,6]. Building on this previous undersea work, the intent of this project is to further our understanding of the potential feasibility of both neutron and capture gamma detection in an undersea environment.

Neutrons from plutonium-bearing SNM near the ship's hull may escape the hull into the seawater. Thermal neutrons will then be absorbed by surrounding materials, including

hydrogen and chlorine in the water, and iron in the ship's steel hull. These absorptions all result in capture gamma emission, generally in the energy range from 2 to 8 MeV, with a mean free path in water of 20-33 cm. According to the experiments conducted by McKay, Schell, and Millett [6], seawater attenuation resulted in a detectable neutron signature out to a distance of approximately 15 cm while the capture gamma signal was detectable out to approximately 50 cm from the hull.

This project continues the previous work conducted by McKay that compared two different SNM detection schemes that might be employed by an unmanned underwater vehicle (UUV): (1) equipped with a neutron detector to directly detect neutrons from SNM and (2) equipped with a gamma detector to detect capture gammas resulting from neutron capture in seawater. There were three weaknesses identified in the previous study that are improved upon. First, the source is located in air and the detector submerged in water (as in the anticipated scenario), whereas the previous study had these reversed. Second, the steel representative of hull material was placed between the water and the source, whereas the previous study had no hull material. Lastly, the neutron source used in the current study is a ^{252}Cf spontaneous fission source, with neutron energies similar to that of ^{240}Pu, whereas the previous study used an AmBe (α,n) source. If a model with ^{252}Cf is validated, then further research would compare results from capture gammas produced by ^{240}Pu.

Experimental Setup, Simulations, and Analysis

This current study uses essentially the same sensors as the McKay experiment. A high purity germanium detector (HPGe) and a ^{3}He neutron detector, each of comparable size, were used, though the sensors will be submerged in water. The experiment includes a ^{252}Cf spontaneous fission neutron source with an emission strength of approximately 3 x 10^{6} neutrons per second. Note that this source strength is several times larger than the neutron emission anticipated from a formula quantity [7] of weapons-grade plutonium. Figure 1 indicates normalized neutron energy spectra from AmBe, ^{252}Cf, and ^{240}Pu neutron sources. This figure indicates that the californium spontaneous fission source is a better representation of the plutonium neutron spectra than the previously used AmBe source.

The undersea environment was be simulated with a 55 gallon polyethylene drum filled with artificial seawater, similar in mineral content to actual seawater but lacking biologics. A ½-inch thick sheet of steel (0.5 percent carbon-steel) was placed between the source and the water drum to simulate the hull of a vessel. Thermal neutrons interact with the iron atoms in the steel and cause an increase in neutron capture and a change in gamma radiation. Two models were created in the Monte Carlo Neutron Particle code (MCNP) [8] to indicate the difference in the capture gamma signature based on the presence or absence of a steel plate. An HPGe detector was modeled at a distance of 9 cm from the hull, in the configuration indicated in Figure 2. The boxed region focuses on the energies between 6-8 MeV where the additional capture gammas from iron are evident. The MCNP model of the experimental configuration was then used to simulate the detector at various distances from the vessel hull.

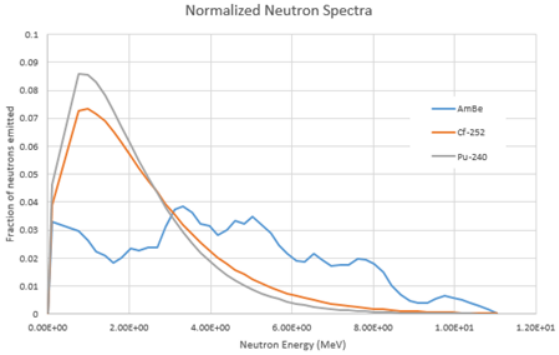

Figure 1. Normalized neutron energy spectra for ^{252}Cf, ^{239}Pu, and AmBe.

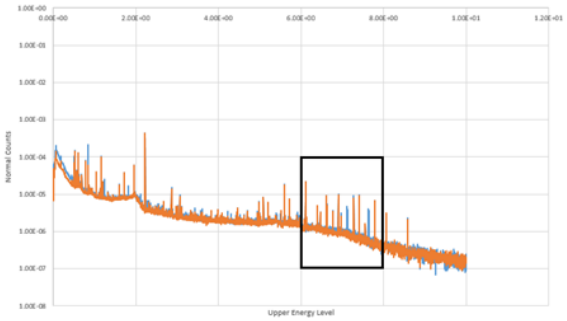

Figure 2. MCNP results of HPGe detected capture gammas with (blue) and without (orange) a steel plate.

The ^{252}Cf source was mounted underneath the steel plate to simulate SNM in the bilge area of a ship. Neutrons traveled into the steel and water by different paths and eventually were absorbed, creating the measured capture gamma signature. The respective detectors were submerged at various depths (representing distances from the hull) and measured the gamma or neutron environment.

Results

Data was collected at three different depths with a 24-hour background sample and five-minute tests as shown in Figure 3. The background and sample data were normalized to show the significance of the surrogate SNM present by the signal of gamma rays from neutron interaction and the source itself. Chlorine and Iron peaks were identified in the 6 to 8 MeV range due to the capture of the ^{252}Cf neutrons. There was no significant

background energy at the 6 and 8 MeV energy levels, making these excellent ranges for material presence discrimination and aligned with the MCNP prediction. While capture gammas were identified at energies greater than 8 MeV, they appear to be less useful in SNM discrimination due to their weaker peak.

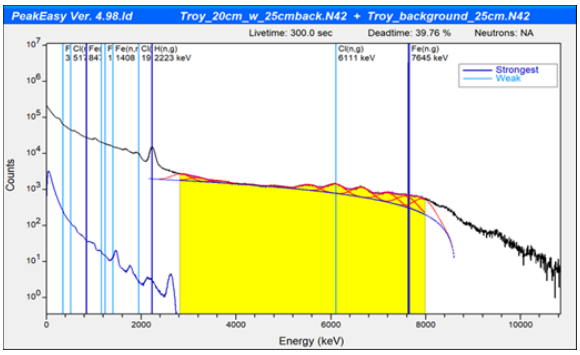

Figure 3. This particular collection of data was at 20 cm. The highlighted region identifies the SNM.

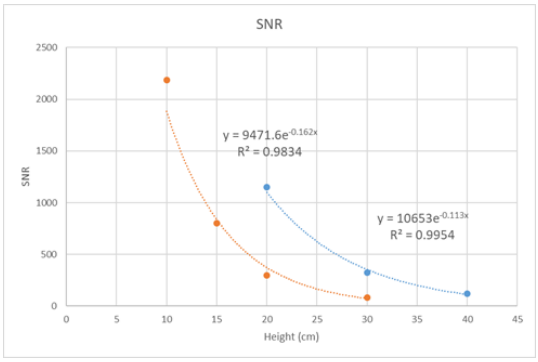

Figure 4. The Signal to Noise Ratio between neutron (orange) and gamma (blue) detection.

The results of these simulations and experiments provide a better characterization of the combined undersea neutron and capture gamma signatures anticipated from a plutonium-bearing SNM source located within a steel hull. Similar to previous work, a crossover point was found, where, at some distance from the hull, the capture gamma signature became more observable than the neutron signature. The gamma detection can also track more than just the parent reaction gammas, but also the decay of daughter products and their levels of energy, making discrimination of SNM by gamma spectrometry more effective.

Figure 4 concludes that the gamma detection has almost four times the signal to noise ratio at 20 cm than the neutron detection from the source. This suggests capture gamma detection represents a more capable method of SNM detection in the undersea environment.

This improved characterization will be useful in the development of protocols and the design of detection systems for use on UUVs, including both determination of detector type and the identification of energy regions of interest. Finally, having a validated model of this near-hull undersea environment will support further studies for system optimization or signal exploitation without the need for full experimentation.

Acknowledgement

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